USING GRAVITY FOR SUBSURFACE IMAGING AT SHIP ROCK, NEW MEXICO

SARINA YOSPIN, Carleton College
BRETT MAYHEW, Whitman College
Research Advisors: Charly Bank
Mary Savina
Kevin Pogue

INTRODUCTION

Ship Rock is a large brecciated volcanic feature flanked by prominent dikes. Many volcanic neck-radial dike systems geometrically resemble Ship Rock, so its origins are often assumed to be the same. Recently, however, the volcanic neck interpretation of Ship Rock has been called into question by the competing model of a dike and diatreme system (Semken, 2003; Delaney, 1987). A diatreme is defined as a volcanic vent or pipe drilled vertically through the surrounding rock by the explosive energy of a gas-charged magma (McCallum and Mabarak, 1976). It is hypothesized that the dikes formed radiating up and in towards what is now Ship Rock and either preceded or followed the diatreme explosion that created Ship Rock itself.

Because the different emplacement sequences would generate different subsurface geometries, this study aims to answer the questions regarding Ship Rock's formation through a gravity survey and modeling. Gravity anomalies, as detected on the surface using highly sensitive gravimeters, could indicate the presence and location of dense subsurface dikes and other igneous features. A better understanding of the geometry of the explosion chamber and the buried dikes could provide evidence in support of this diatreme model.

This study establishes the presence of two significant gravity anomalies at Ship Rock, models what subsurface features they may reveal, and discusses which model of Ship Rock's formation is supported by the gravity data.

GRAVITY

TThe competing models for emplacement (volcanic neck or diatreme; dike-fed diatreme or diatreme pre-dating dikes) can be tested by using modeled subsurface imaging. Imaging can show the subsurface bodies' shapes and locations in the volcanic field, and the root contacts of dikes and diatreme or magma chamber at depth. Gravity varies significantly in space from the standard 9.8m/s^2, due to several factors. Gravimeter machine drift, earth's tidal variations, latitude of sampling site, height of the sampling site above mean sea level and above the earth's averaged ellipsoid height, the variable thickness and density of the crustal slab, large-scale regional features and topographic relief all impact gravity readings. To account for each of these sources of variability, and isolate the effect of subsurface density variations on gravity, several layers of corrective formulae are applied to field data. A gravity anomaly is the measured gravity value after the other effects have been accounted for. Gravity values are reported in mGal (milligals), or 10^{-5} m/s^2.

Testing with gravity is the method of this study because of its capabilities for accurate subsurface imaging. This technique is especially important at Ship Rock, where surveys involving more invasive methods like drilling or coring would be both uneconomical and highly disrespectful and inappropriate on these lands sacred to and owned by the Navajo Nation.

METHODS

Two LaCoste and Romberg Model G gravimeters were used in this study (Fig. 1). Each gravimeter houses a mass suspended on a spring. After the device is precisely leveled on the ground, and the mass is given at least ten seconds to stabilize, the spring's extension is measured and converted to the gravity field strength in that location.

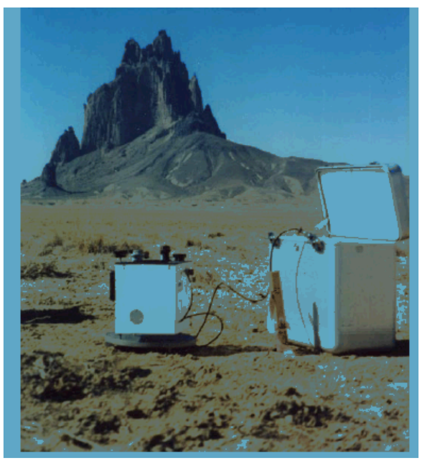


Figure 1.
The La Coste and Romberg Model G gravimeter must be set on a level plate to measure downward extension of the machine's internal spring, used as a measure of gravity field.

Gravity readings were taken at .3 km (300 m) spacing in a 12 km E-W x 11 km N-S area along several roads around Ship Rock, creating a network of approximately E-W and N-S striking gravity profiles. The data collection lines were selected to construct a loose grid around the Ship Rock diatreme and its associated dikes, with over a hundred readings taken along 10 sampling lines.

Horizontal position was taken at each measurement site using Trimble roving GPS units. Most of the GPS error can be corrected with differential processing, reducing error to roughly 1.3 m. For even greater accuracy, the carrier phase is used, reducing error to 10 – 20 cm, post-processing. Total Station surveying equipment was used to obtain the vertical position of each gravity station site within 10 cm accuracy.

GRAVITY DATA CORRECTION

In order to isolate the effects on gravity anomalies of high-density subsurface bodies, all other sources of variation must be adjusted out of every gravity datum. To account for these unrelated factors, a value must be either added to or subtracted from the gravity reading as taken in the field.

Drift correction adjusts for regular drift in the machines and for tidal effects. Latitude correction accounts for the distance away from the equator, and the free-air correction compensates for the height of the gravity station above a reference elevation regardless of terrain, as if the gravity station were floating in "free air." The simple Bouguer correction adjusts the crustal plate to an even Bouguer density and thickness. The regional correction compensates for larger trends in gravity, allowing local-scale anomalies to be isolated, and terrain corrections remove the effects of above-surface materials' effects on subsurface anomalies. Adjusting our raw field values for all these expected effects provides us with Bouguer gravity values. If terrain correction has not been done, we call them Simple Bouguer gravity values.

RESULTS

A high gravity anomaly would indicate that the detection instrument was situated above high-density material. Solid minette (as in the dikes) is the densest material this study will likely encounter; minette tuff breccia, the material of the diatreme and likely of its feeder pipe, is less dense than pure minette; and the Mancos shale country rock is far less dense than either igneous material.

Figure 2 shows a contour map of Simple Bouguer gravity data, with a profile across the centers of detected gravity anomalies. Featured are two main anomalies: a steep high and a slight low in the northwest sector of the study area, with an accompanying profile of gravity data across the anomalies (Fig. 2).

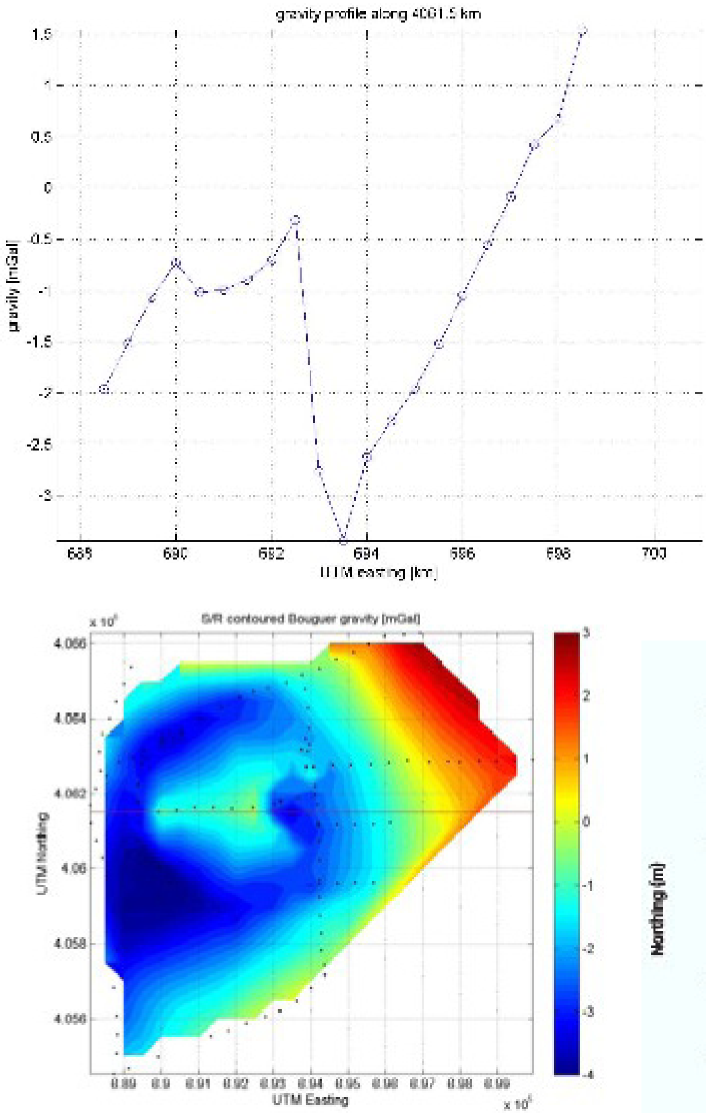
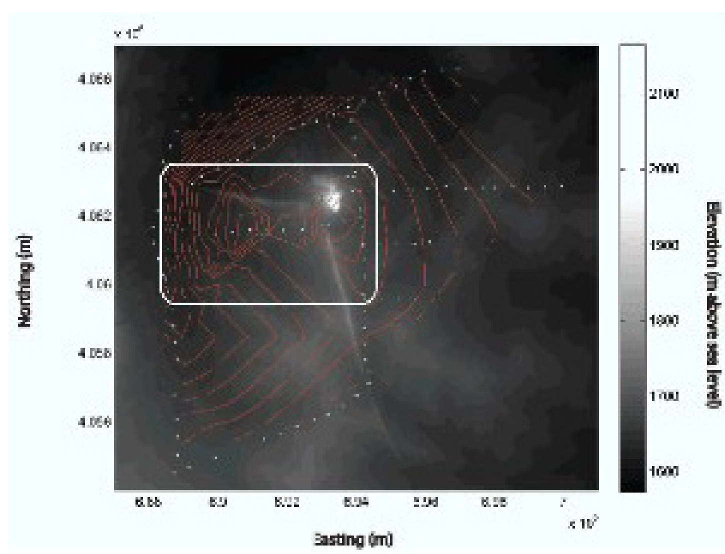


Figure 2.
The profile of Simple Bouguer gravity data along the Northing = 4061 km line intersects the centers of the high and low gravity anomalies studied (top). The location of this profile line is shown at bottom on the color contour map of Simple Bouguer data collected.

The roughly circular -.25 mGal high extends about 2 km E-W and 2.5 km N-S. Just east of this, a slight gravity low of -3.5 mGal has a 1 km E-W, 2.5 km N-S extent. To the northwest of the high anomaly, gravity vales decease sharply, but on all other sides of both anomalies gravity values decrease at a fairly steady rate. The steep decrease in gravity values in the NW corner of the study area is likely because of the presence of the Rattlesnake anticline (Delaney and Pollard, 1981).

Given the distribution of stations around them, the anomalies are well constrained and credible. Figure 3 shows the corrected and contoured Bouguer gravity data superimposed onto a DEM of the Ship Rock area. As seen on this map, the gravity high falls west of Ship Rock and the slight gravity low is located at Ship Rock itself.

Figure 3.
Simple Bouguer gravity values show their relation to Ship Rock when laid over a Digital Elevation Map (DEM) of the area. The bounded area contains the two significant anomalies investigated in this study. (Modified from Bank, 2007)



DISCUSSION

Interpretation: Buried Feature

A subsurface feature does not usually exceed in depth the width of its gravity anomaly as detected at the surface; as both detected gravity highs are expressed as narrow-range surface anomalies, their depths of emplacement should be quite shallow, likely less than 2 km (Everson and Roggenthen, 1988). The gravity high may indicate a dense subsurface feature, and the gravity low is likely caused by Ship Rock itself.

Given the position of this anomaly, the gravity low is most likely a result of the effects of Ship Rock's aboveground mass on gravity signature. To estimate the gravity effect of Ship Rock, and perform a rough terrain correction, the feature was approximated by a 500 m cube, and the gravity effect was calculated. A density of 2670 kg/m^3 (standard Bouguer density) was assumed. Terrain correction values for stations close to the diatreme actually show a -.25 mGal gravity low. As expected, this terrain correction basically removed the simple Bouguer gravity low S of Ship Rock

The gravity high could be explained in light of the stratigraphy of the area. Stratigraphic surveys have estimated the thickness of the Mancos shale at 600 m near Ship Rock given present-day surface elevation (Semken, 2007). Perhaps in the space available at the contact between the Mancos and the underlying rock, at a depth of roughly 600 m, these features were emplaced, taking advantage of the roughly horizontal plane of weakness. Specifics of the shape of such a feature cannot be discerned from the data, but the feature would need to be very broad to create an anomaly similar to the observed gravity profile for the high; perhaps a thick minette sill could produce such data. A ~ 600m emplacement depth at this contact would fit the observed data relatively well, and offers one explanation for the feature's burial depth.

To better fit the observed gravity data, however, this dense subsurface feature must be modeled at a greater depth. The gravity high to the west of Ship Rock could be the result of the stratigraphy in the area, but may be better explained as evidence of a small magma chamber. To obtain a gravity profile such as one in Figure 2, the mass causing the anomaly must be fairly large and deep because of the large width of the high anomaly. Using a sphere as the shape of the mass, its depth is calculated as 2000 m, with a radius of 950 m, assuming a difference in density of 1000kg/m3 between Mancos shale and minette. The resulting sphere, shown in Figure 4, gives a gravity profile to the measured one.

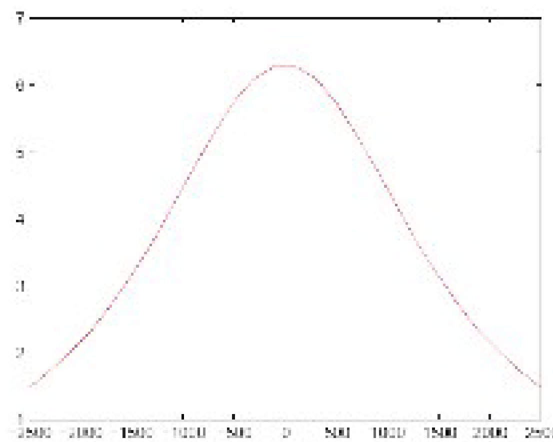


Figure 4.
The gravity profile produced by a modeled sphere of 950 m radius and 2000 m burial depth shows that a small magma chamber fits observed data well, as this profile is similar to the anomaly profile produced by observed data (see Figure 2).

Another possibility is that this spherical mass is actually a shallower doughnut-shaped mass representing an up-warping of the basement rock, which is highly dense, as metamorphic rock can reach densities near those of volcanic materials like minette. The depth to basement is ~ 1200 m, making this a viable solution as well (Semken, 2007).

CONCLUSIONS

TThis study's purpose was to investigate two significant gravity anomalies around Ship Rock, and to determine what model of formation these features best support. The survey detected one anomaly that likely shows evidence for a buried dense body, and one anomaly caused by Ship Rock itself. The buried body is almost certainly not a narrow dike or a continuation of the diatreme pipe of Ship Rock, but could be explained by any of three proposed models.

The first model explains the anomaly as resultant from a broad dense body emplaced at the 600 m depth where Mancos shale meets basement material. The second model explains the gravity anomaly as the result of a small magma chamber with a 950 m radius, buried at 2000 m; a magma chamber of this size may still be small enough to support a dike and diatreme model of formation, as opposed to the volcanic neck model. The third model to explain the high anomaly is that an up-warping of dense basement rock, in a donut shape, located at a shallower depth. Any one of these scenarios is equally possible, as we have no other immediate data to contribute to a solution.

ACKNOWLEDGEMENTS

Field work on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department, and persons wishing to conduct geologic investigations on the Navajo Nation must first apply for, and receive, a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 88515, telephone (928) 871-6587.

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